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Transmission Efficiency Optimization for the operation of double-circuit Overhead Lines

Thales M. Papazoglou

Electric Power Systems Lab (EPSL), Electrical Engineering Department,
The Technological Educational Institute of Crete
E-mail: thales@teemail.gr

Abstract. Nowadays the question of improving overhead-line (OHL) operation efficiency is more than ever considered as a very critical issue. This is because power losses have recently acquired an extra cost due to the CO_2 release penalty. It is well known that a good portion of the electricity required to operate a power grid is spent as OHL power losses. In this paper the key points of the maximum OHL transmission-efficiency theory are reviewed. OHL loading enabling the maximum transmission efficiency is given. With a case study it is then shown how to optimize the double-circuit OHL transmission-efficiency for the periods of OHL off-peak loading. The OHL transmission-efficiency vs. OHL loading curves of the OHL is presented and the change in the character from capacitive to inductive with an increasing OHL load is illustrated. Potential transmission-efficiency gains in percentage points are calculated. Conclusions of practical importance are drawn both for OHL design purposes as well as for its operation optimization.

Key words: transmission efficiency optimization, double-circuit OHL, OHL change-of-character curves

1 INTRODUCTION

It is well-known that about 3 % of the power generated in an Electric Power System (EPS) is lost in transmission (while about 6 % are distribution losses). It has been noted that *6 % of electricity is lost on a 1000 km OHL.* About half of the transmission power is lost due to High-voltage (HV) OHL losses. These losses are part of the operating cost of transmission Companies. Nowadays, the pressure to reduce electric power losses is greater than ever before because of the constraints imposed by the deregulated market as well as by extra costs due to the excessive CO_2 release penalty.

OHL efficiency depends on its loading. It can vary from zero, when OHL is in its idle state, i.e. energized but under no load, to a maximum value. Under the nominal load, the OHL efficiency is quite high. As it will be clarified in the next section, there is a certain characteristic load that corresponds to the maximum OHL efficiency. Therefore, the greater the difference between the actual OHL load and the characteristic one, the greater is the efficiency margin between the actual and the maximum OHL transmission efficiency.

In the case of a low-to-medium loaded double-circuit OHL, as we will see in Section 3, one can increase the OHL transmission-efficiency by either dividing the load between the two circuits or concentrating the load into one circuit depending on the relation between the actual load and the characteristic OHL load enabling maximum efficiency.

2 SOME ELEMENTS OF THE MAXIMUM OHL TRANSMISSION-EFFICIENCY THEORY

In 1994 the author [1] comprehensively formulated the theory of OHL maximum transmission efficiency. In reviewing its elements I will start from the well-known equations of a long OHL having ‘1’ as the sending end (or OHL start) and ‘2’ as receiving end (or OHL end):

$$V_1 = A \odot V_2 + B \odot I_2$$
$$I_1 = C \odot V_2 + A \odot I_2$$

where V is the OHL phase voltage and I the OHL current and A, B, C are the so-called generalized circuit constants of a symmetrical OHL having the following expressions:

$$A = \cosh(\gamma l)$$
$$B = Z_0 \cdot \sinh(\gamma l)$$
$$C = \frac{\sinh(\gamma l)}{Z_0}$$

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expressed in terms of the OHL parameters, i.e. OHL characteristic impedance Z_0, propagation constant γ, and OHL length l.

The maximum OHL efficiency is computed with the formula below:

$$\eta_{\max} = |A|^2 + \mathrm{Re}(BC^*) + \\ -\sqrt{4\,\mathrm{Re}(AC^*)\,\mathrm{Re}(BA^*) - \mathrm{Im}^2(BC^*)}$$

where "| |" denotes the magnitude of a complex number, Re and Im denote the real and imaginary parts of a complex number, and asterisk "*" is used to denote the complex conjugate.

This maximum OHL transmission efficiency is reached when the OHL load corresponds to the equivalent impedance with a magnitude of:

$$\zeta = \sqrt{\frac{\mathrm{Re}(BA^*)}{\mathrm{Re}(AC^*)}}$$

and with phase-angle θ such that:

$$\sin\theta = -\frac{\mathrm{Im}(BC^*)}{2\sqrt{\mathrm{Re}(AC^*)\mathrm{Re}(BA^*)}}$$

Now, if V_L is the OHL voltage at the load, then the OHL load corresponding to the condition of the maximum transmission-efficiency is:

$$P_e = V_L^2\,\frac{|A|^2 + \mathrm{Re}(BC^*) - \eta_{\max}}{2\,\mathrm{Re}(BA^*)}$$

As it turns out, OHL characteristic load P_e, which is computed solely from the OHL electrical parameters, irrespective of the actual load coefficient, indicates where the OHL transmission-efficiency is maximized.

3 OHL TRANSMISSION-EFFICIENCY CURVES

For a 220 kV 250 km long OHL used in a case study with parameters:

$$\gamma l = 0.2756\angle 85^\circ$$
$$Z_0 = 408.25\angle -4^\circ\,\Omega$$
$$A = 0.963\angle 0.387^\circ$$
$$B = 111.044\angle 81.13^\circ\,\Omega$$
$$C = 6.66\cdot 10^{-4}\angle 89.13^\circ\,\mathrm{S}$$

the maximum OHL transmission-efficiency is 97.13 %, computed with the formula given in the previous section. Irrespective of the load, this means that this value for the OHL transmission-efficiency is the highest possible. As OHL is loaded up to its rated capacity, its transmission efficiency drops (see Figure 1). Characteristic load P_e (corresponding to the maximum transmission efficiency) is:

$P_e = 41.31$ MW.

For a double-circuit OHL this will correspond to a total of 82.62 MW. So if a double-circuit OHL with specifications given above, is to deliver more than 83 MW; sharing this load equally between the two circuits increases its transmission efficiency. Irrespective of the load coefficient as seen from Transmission Efficiency Curves (TEC) shown in Figure 1.

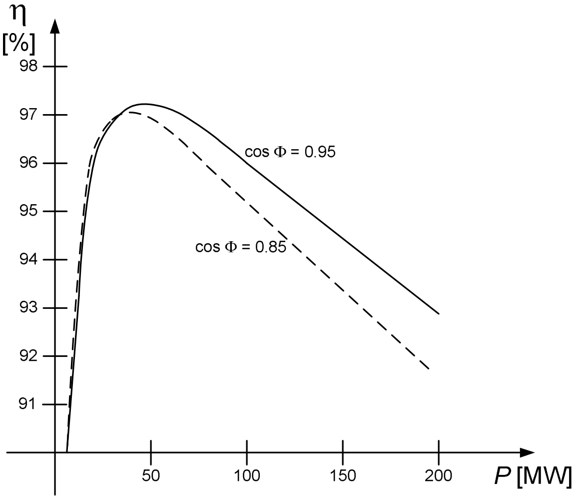

Figure 1. Transmission Efficiency Curves (TEC)

TECs shown in Figure 1 are in the case-study drawn for a single-circuit OHL. Each TEC corresponds to one load coefficient (0.85 or 0.95 inductive as indicated in the figure). So, if delivering 200 MW of the load at a 0.85 load coefficient only with one circuit, the OHL transmission-efficiency will be 91.24 %. If the same load is equally divided between two circuits, the transmission efficiency will be 95.2 % (roughly a 4 % increase in the OHL transmission-efficiency). However, if there are 40 MW to transmit and delivered over two circuits (20 MW each), the OHL transmission-efficiency will be 96.32 %, while if delivered over just one circuit the it will be 97 % (very close to the maximum).

An interesting TECs feature is their horizontal displacement (see Figure 1) resulting in change in the OHL ohmic resistance. For example, if the ohmic resistance in the case-study was half of the assumed one, i.e. P_e = 57.63 MW, there would be a substantial increase and consequently displacement of TECs to higher line loads. In such case, the maximum OHL transmission-efficiency would be 97.97 %.

4 OHL CHANGE-OF-CHARACTER CURVES

The OHL character changes from capacitive to inductive depending on variations in loads changing from light to heavy ones. In our particular case-study, changes in the character are illustrated with Overhead Line Change-of-character Curves (OLCC) shown in Figure 2.

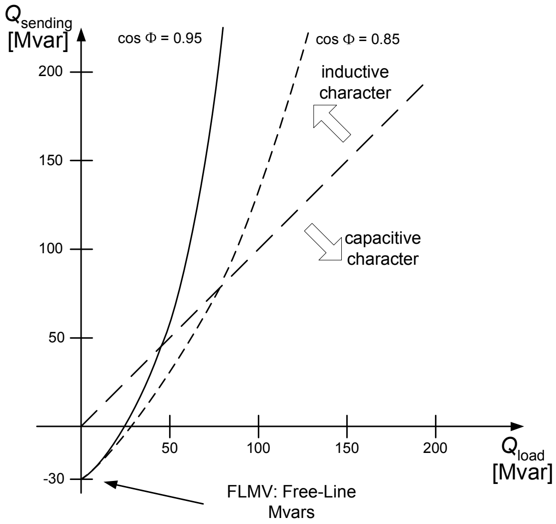

Figure 2. Overhead Line Change-of-character Curves (OLCC)

Each OLCC corresponds to one load coefficient. There are two OLCC curves shown in Figure 2, one for a 0.95 and the other for a 0.85 inductive load coefficients. The OHL characteristic is capacitive for light loads and inductive when its load increases, which is clearly seen in OLCC. The dashed line is the Overhead Line Neutral Line (OLNL) on which the OHL character is neutral. For example, for the load coefficient of 0.85, the crossing of the OLCC with the OLNL corresponds to an OHL load of about 120 MW (a bit higher than the surge-impedance OHL load: P_{SIL} ~ 119 MW) for which sending Mvars and load Mvars are both equal, i.e. 74.5. An interesting and expected OLCCs feature is that, they all converge to a point on the Sending-Mvar (vertical) axis which is a Free-Line MVars (FLMV) point with a numerical value equal to the Mvars absorbed by OHL under the nominal voltage in its off-load state. In our case-study, the FLMV point is at -33.48 Mvar (see Figure 2).

5 BENCHMARKING A DOUBLE-CIRCUIT OHL FOR MAXIMUM EFFICIENCY

In Section 2 above, the characteristic load for one circuit corresponding to the maximum OHL transmission-efficiency is given, using symbol P_e. In case of an entire double-circuit OHL, the characteristic load corresponding to the maximum transmission efficiency is:

$$P_{dl} = 2\odot P_e.$$

This can be used as a yardstick or benchmark for maximizing the OHL efficiency during operation.

To provide an example, let us consider again a double-circuit OHL with parameters given in Section 3 above. In this case the maximum efficiency yardstick is $P_{dl} \approx$ 83 MW. When the transported load is higher than the yardstick, then the load should be divided and delivered by both circuits to get maximum efficiency. For example, for a demanded load of 200 MW and load coefficient 0.85 inductive, if the load is divided between the two circuits, then the transmission efficiency is 95.21 %. If the whole load is carried by just one circuit, OHL transmission-efficiency drops to just 91.24 %. On the other hand, for a load of only 50 MW and load coefficient 0.85 inductive, the whole load should be carried by just one circuit with efficiency of 96.9%, instead of dividing it between both circuits which leads to efficiency dropping to 96.7%.

For multi-circuit OHLs, analogous maximum-efficiency yardsticks can be used in the form of:

$$P_{ml} = m\odot P_e$$

where m is the number of circuits.

6 FURTHER INVESTIGATIONS

Efficient managing the OHL environmental impacts is nowadays of a great concern. OHL electrical losses and harmful CO_2 emissions into air are subjects needing to be seriously investigated. Ways to minimize the OHL environmental impact can be found by investigating both the impacting OHL parameters during the design stage and in providing appropriate compensation (series, or shunt) strategies during OHL operation enabling reduction in operation losses.

7 CONCLUSIONS

The paper addresses OHL transmission-efficiency for being very important issue of the electricity supply industry. Elements of the maximum OHL transmission-efficiency theory are reviewed. It is shown how to deliver the power over circuits of off-peak loaded double-circuit OHL at highest possible OHL transmission-efficiency rates. An easy to use yardstick is proposed as a maximum efficiency benchmark for the double-circuit or multi-circuit OHL. Potential gains in OHL transmission-efficiency are shown to be substantial. The change-of-character from capacitive to inductive depending on the size of the transmitted load is illustrated. Further investigations are suggested both for proper OHL-parameter design and OHL operation compensation strategies.

REFERENCES

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Thales M. Papazoglou, PhD was born in 1945, in Iraklio Crete. He has been a Professor of Electric Power, and Director of Electric Power Systems Laboratory at the Technological Educational Institute of Crete for 35 years. He had been very active, and continues to be, for a good number of years in Cigre and has actively contributed in a total of ten Working Groups and Task Forces therein. He is currently the Convener of WG C2.13 on Voltage and Var Support in System Operation. Over the years, he has published a large number of papers, textbooks, and has often contributed to major international conferences. He is a ranking member of the international committees of the annual Universities Power Engineering Conference (UPEC), and has been, for a number of years, of the Power Grid Europe. He is the Steering-Committee Convener of DEMSEE, the annual Deregulated Electricity Market issues in South Eastern Europe Conference – which he has founded in 2005.